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ELECTRICAL AND THERMAL CONSIDERATIONS IN THE DESIGN OF ELECTROEXPLOSIVE DEVICES

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ABSTRACT

Electrical and thermal considerations in the design of electroexplosive devices are discussed, with emphasis on means of complying with the "1 amp, 1 w, no-fire" requirement of many recent standards and specifications, yet retaining sufficient pulse-energy sensitivity to be fired by guided missile fuze circuitry in current use. Included are discussions of the implications of the general, lumped parameter electrothermal equation for input characteristics of initiators, the analogy of electrical and thermal conductivity, and the control of gross heating of initiators. A set of units for convenient computation of thermal properties of initiators is proposed, conversion formulas are given, and values for frequently used materials are tabulated in the suggested units. Equations are derived for the design of bridgewires of various length/diameter ratios and film bridges. Effects of plug and terminal materials and design, and the choice of explosive are discussed. It is possible, by the choice of materials, dimensions, and configuration, for the designer to predetermine energy, current, and power sensitivity independently over a wide range of values.

FOREWORD

The work described in this report was performed during FY 1964 by the R. Stresau Laboratory, Inc., Spooner, Wisconsin, as part of Contract N123(62738) 31089A with the Naval Ordnance Laboratory, Corona (NOLC), California. The report is printed substantially as submitted by the author in fulfillment of contractual requirements.

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INTRODUCTION

Widespread concern regarding the hazards of premature initiation of electroexplosive devices (EEDs) as the result of electromagnetic or electrostatic conditions inherent in ordnance applications has led to the promulgation of a number of specifications and standards limiting the sensitivity of EEDs. Although their applicability to systems protected by out-of-line safety and arming (S-A) devices and electrical and magnetic shielding is somewhat questionable, considerable pressure for such application is evident. Application of some specifications intended for general use (Ref. 1) would result in the disqualification of practically all EEDs currently used in fuzes. A more serious effect would be the disqualification of existing firing circuits designed for use with the relatively sensitive EEDs in current use, and the need to replace them with the larger and heavier units necessary for the less sensitive EEDs that meet these recently established criteria. However, more detailed consideration of the characteristics and limitations of firing circuits presently used, and of the criteria set forth in recent documents, indicates that they are not necessarily incompatible. Many firing circuits in current use are essentially pulse generators, capable of quite substantial output of instantaneous current and power, but somewhat limited amounts of energy per pulse, whereas the recently established criteria place lower limits on power and/or current required to fire, with no reference to energy sensitivity. For example, a typical firing circuit might have output current capability of over 50 amp and output power in excess of 3 kw, but energy output of only 10,000 or 20,000 ergs. Such a circuit should be capable of firing an EED that meets the "1 amp, 1 w, no-fire; 5 amp, 5 w, all-fire" requirements of Reference 1, except that most EEDs that have been developed to meet these requirements have energy needs substantially greater than 20,000 ergs. As will be shown below, this need for high energy is not necessarily inherent in hot-wire EEDs that meet the requirements of Reference 1, but results from the application of a widely prevalent approach to the development of such initiators. In principle, as will be shown, power sensitivity and energy sensitivity are subject to independent control by the designer's choice of materials and dimensions. In practice, some of the designs are beyond the state of the art of the fabrication techniques that are economically feasible for EED production. However, several quite feasible designs are shown herein to combine predicted specification compliance with relatively low-energy requirements.

The input characteristics of thermal EEDs (as distinguished from exploding bridgewire devices) are determined by the interaction of

resistive heating, heat transfer, and reaction kinetics. A complete and rigorous analysis of even the simplest EED in these terms would require an extensive (and expensive) computer program as well as data that are not available. However, thermal EEDs have been found to be particularly susceptible to analysis in terms of simplified models, which have been found to be extremely useful (within their intended ranges of application) in the design of EEDs to meet specified input requirements and for the prediction of performance and behavior of existing EEDs. The analyses presented herein are based on simplified models of suggested designs that would comply with the requirements of Reference 1 and yet fire from the output of existing circuits. In addition, this report includes experimental data that are in general agreement with one of the analyses. For each design concept considered, the analytical results are used to calculate dimensions that will be expected to result in an EED of desirable input characteristics, in the terms of reference that have been outlined. Fabrication techniques for EEDs with these calculated dimensions will be the subject of a future report.

GENERAL PRINCIPLES OF ELECTROEXPLOSIVE DEVICES

As with any explosive initiation system, the threshold condition for initiation is that at which heat is liberated by the explosive decomposition faster than it is dissipated from the nucleus of reaction. This, of course, results in a temperature increase and, in view of the exponential relationship between reaction rate and temperature, an exponential increase in reaction rate. If the explosive is assumed to be a continuous solid medium in which the dominant heat transfer process is conduction, and which reacts in accordance with the Arrhenius equation, it is possible to express this process in a differential equation that can be solved numerically to yield critical temperatures for various reaction nucleus dimensions (Ref. 2). However, the assumptions mentioned are so unrealistic in their representation of granular solid explosives that the numbers obtained are meaningless (Ref. 3). On the other hand, if the magnitudes are ignored, the relationships predicted by such calculations have been verified by any number of experiments (Ref. 3-6). In Reference 4, it was pointed out that such solutions indicated that the inverse of the threshold temperature should vary with the logarithm of the reaction nucleus dimension. Experimental data for hot-wire EEDs gave straight lines when critical temperatures were plotted as a function of bridgewire diameters. Moreover, activation energies obtained from the slopes of these lines were in excellent agreement with those obtained by other investigators using very different techniques (Ref. 5).

Although the considerations discussed above indicate that the threshold temperature for initiation of an EED varies as an inverse function

of the bridgewire diameter (and also of the time the temperature is sustained), this variation in temperature over the usual range of EED designs is small enough so that the assumption of a single ignition temperature for each explosive material can be very useful. Kabik, Rosenthal, and Solem (Ref. 7) combined this assumption with the equation

$$C_p \frac{d\theta}{dt} + \gamma\theta = P(t) \tag{1}$$

where

C_p = heat capacity of the bridge system

θ = temperature rise above ambient

t = time

γ = a heat-loss factor

$P(t)$ = time-dependent power input

After experimentally determining C_p and γ for an existing EED (as well as θ_m, the threshold temperature for initiation), they predicted with precision the response to a wide variety of complex input signals.

If Equation (1) is solved for a pulse so short that losses may be neglected, the relationship

$$C_p \theta = \int P dt = E \tag{2}$$

where E is the energy delivered by the pulse to the bridgewire, can be combined with the assumption of a constant ignition temperature to obtain the relationship that the firing energy requirement is proportional to the bridgewire volume (since volumetric specific heat varies rather little from one metal to another). For a rather large range of bridgewire dimensions, the threshold firing energy is given by the empirical equation

$$E_t = 25 + 450\, d_b^2 L \tag{3}$$

where

E_t = threshold firing energy (50 percent point) in ergs

d = diameter of the bridgewire in mils

L = length of the bridgewire in mils

This is applicable to normal lead styphnate flash charges. Although no data are at hand to substantiate this view, it is believed that this

relationship of energy to bridge volume should apply as well to non-cylindrical bridges, such as films and ribbons.

By solving Equation (1) for constant power input, $d\theta/dt$ becomes zero, of course, and

$$P = \gamma\theta \tag{4}$$

The heat-loss factor (γ) is, of course, determined by the bridge configuration, its thermal conductivity, and the heat transfer properties of surrounding materials and components. By manipulation of these factors, the EED designer can vary γ, and hence the threshold power for initiation, over a wide range.

The design concepts considered herein include a few that have been proposed and used to comply with Reference 1, and some that are aimed at such compliance in addition to compatibility with firing circuits in current use. The latter designs employ materials and configurations chosen to maximize γ and limit the volume of the effective bridge.

RANGE OF ELECTRICAL CHARACTERISTICS IMPLIED BY SPECIFICATION

Reference 1 specifies that EEDs shall not fire on 1 amp or on 1 w, but shall fire on 5 amp or 5 w. The two "no-fire" points specified coincide if the resistance is 1 ohm. The two "all-fire" points coincide for a resistance of 0.2 ohm. As Kabik pointed out (Ref. 8), the range of characteristics that will meet the specification can be plotted in coordinates of resistance and current (Figure 1). In view of the inherent variability of all manufactured products, to meet this specification consistently and reliably an EED should be designed with characteristics well within the range shown in the figure. It was suggested in Reference 8 that this figure be used in the selection of input characteristics. Since the largest permissible variation in firing current is 0.2 ohm, this value has been proposed as best adapted to comply with the specifications. However, if the general tendency of statistical response of explosive initiation to relate to the logarithms of input magnitudes is considered, a more appropriate ordinate would be the logarithm of the current, as in Figure 2. A glance at that figure shows that there is little choice between 0.2 ohm and 1 ohm. In this range, of course, the limiting currents are determined by the power limits, and since $P = I^2R$, the ratio of the maximum to the minimum input current allowable for any given resistance is exactly $\sqrt{5}$. Other considerations, such as voltage sensitivity and reduction of penalties for circuit and switching defects, seem to make the upper end of this range (about 1 ohm) the more attractive. However, none of these factors seems sufficiently compelling to fix this resistance as a primary design objective. It is possible that,

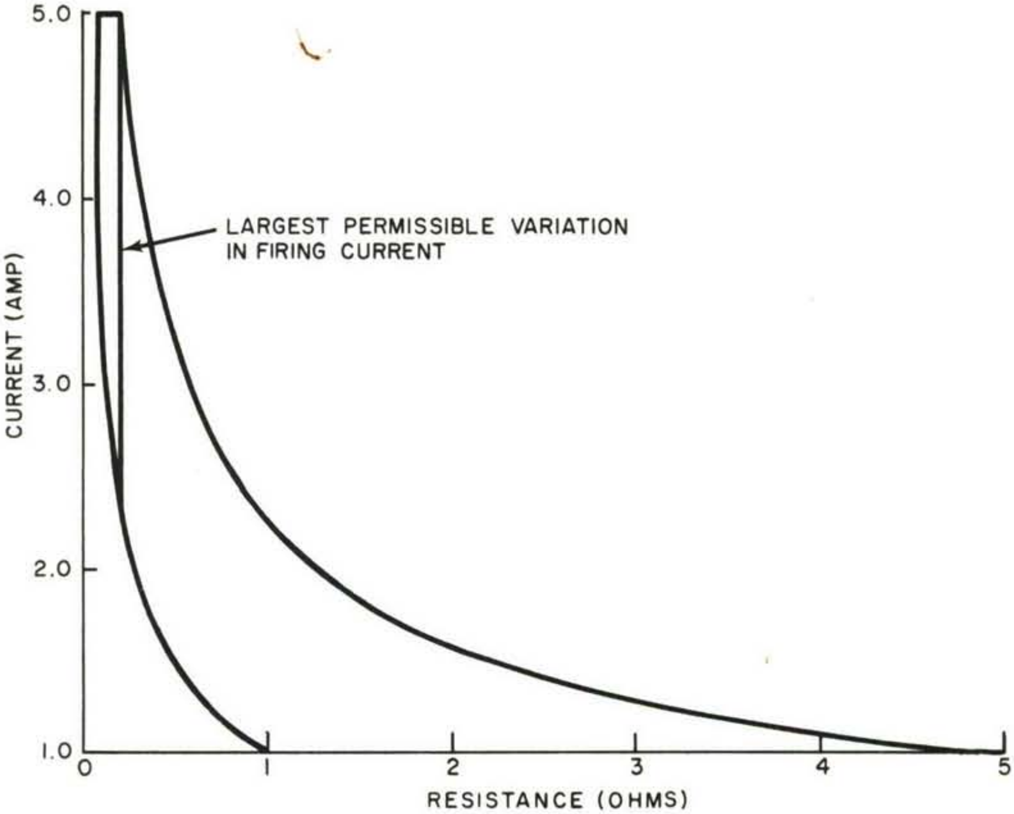

FIGURE 1. Range of Characteristics for EEDs (Current a Linear Function)

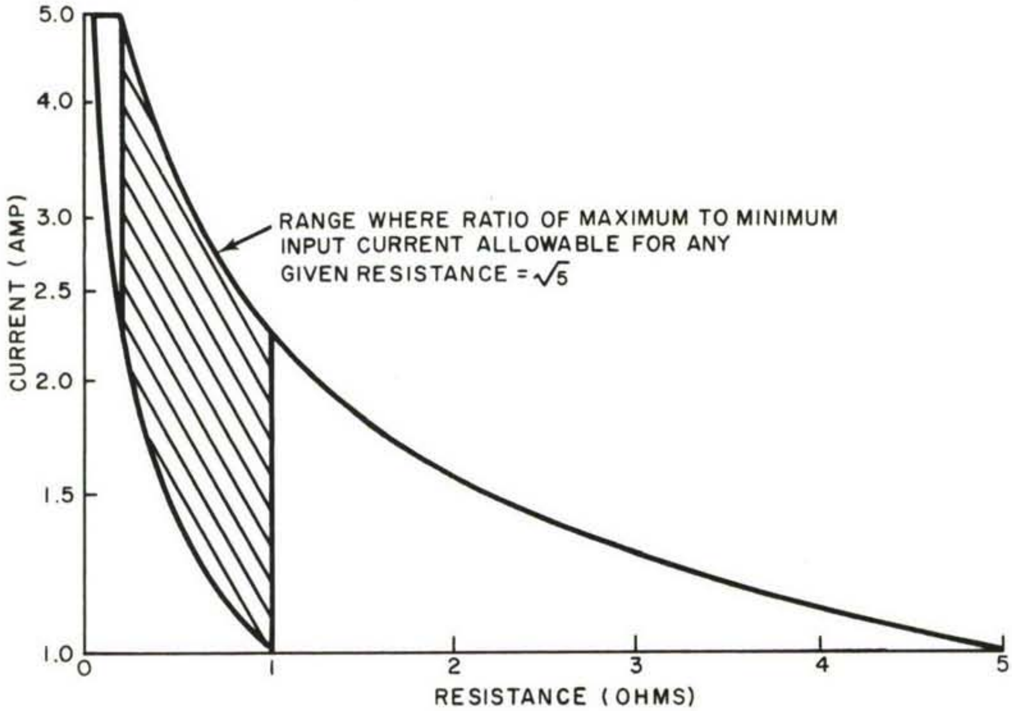

FIGURE 2. Range of Characteristics for EEDs (Current a Logarithmic Function)

for some designs, the combination of materials and dimensions that best combines fabrication feasibility with other desirable properties will turn out to be at either end of this range (0.2 to 1 ohm), or even somewhat outside it. Considerations such as those discussed above can be useful guides to the designer of EEDs. However, it should be borne in mind that the foregoing discussion ignores the rather substantial resistivity coefficients of some bridge materials. These coefficients can be useful design tools also, since resistance can change by factors of up to four or more when the power input is quintupled. Implications with respect to design will be discussed in a later paragraph.

CONVENIENT UNITS AND CONVERSION FACTORS

Because of the magnitudes of the quantities involved, it is convenient to express bridge dimensions in mils, times in microseconds, capacitance in microfarads, potential in volts, current in amperes, resistance in ohms, and power in watts. It would be appropriate, with these units, to express energy in microjoules, but the erg has been used so frequently to express energy input to EEDs that it will also be used herein. Since 10 ergs = 1 μj = 1 w-μsec, the energy (E) in ergs stored in a capacitor of (C) μf capacitance, charged to (V) volts becomes

$$E = 5CV^2 \tag{5}$$

and the energy of a pulse becomes

$$E = 10 \int P\,dt \tag{6}$$

where

E = energy in ergs

P = power in watts

t = time in microseconds

For bridgewires, a convenient unit of volume is the cylindrical mil, which is defined as the volume enclosed in a cylinder 1 mil in diameter and 1 mil long. A rather accurate estimate of the heat capacity of a bridge (C_p) can be made by multiplying the bridge volume in mils by its volumetric specific heat in ergs per cylindrical mil. The volumetric specific heat in calories/mil °C can be obtained from handbook data by multiplying the specific heat by the specific gravity and applying the conversion

$$1\ \text{cal/mil}\,^\circ\text{C} = 0.54\ \text{erg/cyl mil}\,^\circ\text{C}$$

For noncylindrical bridges, the cubic mil may be a more convenient unit of volume:

$$1 \text{ cal/mil } ^\circ\text{C} = 0.687 \text{ erg/mil}^3 \ ^\circ\text{C}$$

For resistance calculations, it is convenient to convert handbook values to ohm mils or ohm circular mils/mil:

$$\begin{aligned} 1 \text{ microhm cm} &= 0.000394 \text{ ohm mil} \\ &= 0.000501 \text{ ohm cir mil/mil, or} \\ &= 0.501 \text{ ohm cir mil/in.} \end{aligned}$$

Heat transfer coefficients are expressed most conveniently in watts/mil °C:

$$1 \text{ cal/sec cm } ^\circ\text{C} = 0.0106 \text{ w/mil } ^\circ\text{C}$$

The foregoing conversions were, of course, from handbook conversion data (Ref. 9) for the more commonly used units. They are offered here for the convenience of EED designers and for reference in later parts of this report.

RELATIONSHIP OF ELECTRICAL AND THERMAL CONDUCTION

Since both thermal and electrical conductivities are proportional to the area of the conductor at right angles to the path of flow, and inversely proportional to the length of the path, for any conductor

$$\frac{P_f}{\theta} = \frac{k\rho}{R} \tag{7}$$

where

P_f = rate of heat flow between two points

θ = temperature differential between the points

R = electrical resistance between the points

k = thermal conductivity of the material

ρ = electrical resistivity of the material

For EED design calculations, it is convenient to express the product ($k\rho$) in ohm watts/°C (although, for tabulation purposes, microhm

watts/°C gives more compact numbers). Published heat-transfer data are often expressed in terms of calories per second, which may, of course, be converted to watts by multiplying by 4.185.

PERTINENT PROPERTIES OF MATERIALS USED IN EEDs

The properties given in Tables 1 and 2 are taken from handbooks (Refs. 9 and 10), manufacturers' descriptions, and other sources. They have been combined and converted to the convenient units mentioned above.

Thermal conductivities and heat capacities of explosives used as flash charges are not readily available in the literature. Reference 11 gives values for thermal conductivities of lead azide and mercury fulminate, which convert to 1.64 and 1.17 μw/mil °C, respectively. These values are given without any data regarding the state of aggregation; however, it is assumed that they are for pressed powders, since they are of the same order of magnitude as the values given for organic high explosives in the pressed granular state. Values for cast explosives are about 10 times higher. No values were found for heat capacities of primary explosives, but they may be presumed to be about 0.2 to 0.4 erg/mil^3 (at crystal density), since values for randomly selected lead, mercury, and silver compounds, as well as those for organic high explosives, fall within this range.

Thermal properties of electrical insulators which have been used or might find application in EEDs are given in Table 2.

A glance at the heat capacity data given in Tables 1 and 2 will reveal that the volumetric heat capacities of all materials, metallic explosives, and insulators vary rather little from one to another. The search for a heat-sink medium with an unusually large heat capacity has rather dim prospects. In metallic conductors, there is a tendency for high resistance alloys to have low thermal conductivity, but this tendency is insufficient to compensate for the increase in electrical resistivity and therefore they do not maintain the nearly constant value of the product ($k\rho$) which obtains for the pure metals and alloys of medium resistivity. In general, this tendency continues for insulators, in that most electrical insulators are also reasonably effective thermal insulators. A notable exception is beryllium oxide, which is comparable with pure metals as a thermal conductor. It may be noted that the ceramics listed have thermal conductivities about 10 times those of the plastics listed. Of course, plastics can be varied in many of their properties by the addition of fillers. One maker of specialized plastics has stated that plastics with thermal conductivities approaching

TABLE 1. Properties of Metals Used in Bridgewires and Other Components

Metal	Volumetric Specific Heat[a]		Electrical Resistivity (ρ)[b,c]		Thermal Conductivity (k),	Electro-thermal Product (kρ),
	$\frac{\text{ergs}/^\circ\text{C}}{\text{mil}^3}$	$\frac{\text{ergs}/^\circ\text{C}}{\text{cyl mil}}$	$\frac{\text{m}\Omega}{\text{mil}}$	$\frac{\text{m}\Omega\ \text{cir mil}}{\text{mil}}$	$\frac{\text{mw/mil}^{d}}{^\circ\text{C}}$	$\frac{\mu\Omega\ \text{w}}{^\circ\text{C}}$
Aluminum	0.534	0.422	1.11	1.46	5.3	5.84
Constantan	0.611	0.481	19.3	24.6	0.57	10.73
Copper	0.672	0.529	0.678	0.862	9.24	6.55
Evanohm[e]	0.597	0.469	52.8	67.2	0.30	20.3
Gold	0.424	0.334	0.96	1.22	7.4	7.2
Manganin	0.547	0.431	17.75	22.6	0.55	9.75
Platinum	0.514	0.405	3.94	5.02	1.76	6.93
Platinum/ iridium(90/10)	0.503	0.397	9.45	12.05	0.79	7.43
Silver	0.432	0.341	0.64	0.817	10.7	6.83
Tungsten	0.452	0.356	2.08	2.76	3.7	8.07
Carbon	0.618	0.486	314	402	0.127	42.7

[a]Specific heats given are estimated averages for 0-1000°C.

[b]Resistivities are at 20°C.

[c]Resistivity values are given in milliohms per mil and milliohm circular mils per mil because the numbers are close to one. For calculations in the suggested units, they should be converted to ohms.

[d]Thermal conductivity values are given in milliwatts/mil because numbers are close to one. For calculations in suggested units, convert to watts.

[e]Evanohm is a proprietary alloy containing 74.5% nickel, 20.00% chromium, 2.75% aluminum, and 2.75% copper. (Data from the booklet "Evanohm," Wilbur B. Driver Company, Newark, N. J.)

TABLE 2. Thermal Properties of Some Electrical Insulators

Material	Volumetric Heat Capacity, $\frac{ergs/°C}{mil^3}$	Thermal Conductivity, $\frac{mw/mil}{°C}$	Temperature, °C		References
			Melting or Distortion[a]	Max. Continuous Service[b]	
Alumina (Al_2O_3)	0.46	0.5	2050	1500	9,12
Beryllia (BeO)	0.528	5.3	2530	--	9
Delrin acetal	0.34	0.0058	160[a]	100	14
Epoxy	0.2-0.3	0.004-0.04	120[a]	80	9,15
Mica	0.4	0.019	--	--	9
Mullite[c]	--	0.05	1770	1650	9,12
Mylar	--	0.0038	250[a]	150	13,14
Nylon	0.3	0.0058	180[a]	150	14
Glass	0.35 appr.	0.011-0.024	--	400-500	9
Polyethylene	0.35	0.0085	40-50[a]	100	14
Polystyrene	0.32	0.003	70[a]	70	14
Phenolics	0.27-0.4	(d)	160[a]	200	9
Porcelain	0.42	0.04	--	1000	12
Quartz (crystalline)	0.34	0.338[e]	1756	--	9
Silica (SiO_2)	0.27	0.026	1670	1620	9
Silicones	0.27-0.4	0.004	--	260	9
Teflon	0.37	0.0064	120[a]	290	14

[a] Distortion temperatures are based on arbitrary test conditions. It is difficult to assess their pertinence to EED design.

[b] Maximum continuous service temperatures are based on judgment of persons unknown. They are included, as are the distortion temperatures, for comparison purposes.

[c] Mullite ($3Al_2O_3$: $2SiO_2$), a ceramic, is available in tubing and other forms.

[d] Properties of phenolics depend upon filler.

[e] Measured along the "c" axis, highest value in this direction.

one-tenth that of metallic aluminum are possible (Ref. 16). (The principal specialty of this company is plastic materials of accurately controlled electrical conductivity, which have been suggested as possible detonator bridge materials.)

GROSS HEATING OF A TYPICAL EED

Most considerations of heat accumulation and dissipation in an EED are concerned with the bridgewire and its immediate surroundings. It is of some interest to consider these matters as they apply to the whole EED, regarded as a lumped thermal mass. Equation (1) is as applicable to such considerations as to the bridgewire system.

A reasonable estimate of the heat capacity of a typical EED can be made rather easily, since the volumetric heat capacities of materials used in EEDs vary rather little from one to another, as shown in Tables 1 and 2. Assuming the average to be 0.3 erg/cyl mil °C, the heat capacity (C_p) of a detonator the size of the Mk 71 (0.195 in. in diameter and 0.5 in. long) is about 5,700,000 ergs/°C (0.57 j/°C). If such a detonator were thermally insulated (that is to say, $\gamma = 0$), the solution of Equation (1) for the 1 w, 5 min test would be:

$$\begin{aligned} C_p\theta &= P(t) \\ 0.57\theta &= 300 \qquad (8) \\ \theta &= 527^\circ C \end{aligned}$$

which would be hot enough to initiate most explosive materials.

Of course such thermal insulation is impossible and can be approached only by such extreme measures as using a Dewar flask. However, this calculation serves to illustrate the importance of heat transfer from the detonator to its surroundings. If we consider a detonator of this kind hanging in free air, γ may be seen to be the sum of the γ resulting from convection, and that resulting from conduction along the lead wires. For the surface coefficient of heat transfer for ordinary surfaces in still air, Reference 10 gives 1.65 BTU/ft^2/hr/°F, which is equal to 0.0063 (w/in.^{2})/°C.

Since the surface area of a detonator of the size mentioned above is about 0.36 in.^{2}, the γ for loss to the air is 0.00227 w/°C. The heat loss through the lead wires can vary enormously over the range of materials and sizes used in current practice for lead wires. Two examples of commonly used combinations of materials and dimensions are 26-gage stainless steel and 20-gage copper, each 4 in. long. By solving Equation (7) for stainless steel, the heat loss through each wire

turns out to be about 0.00001 w/°C, a nearly negligible contribution to the total γ. On the other hand, the heat loss through each of the copper leads is 0.00215 w/°C. Adding the surface losses to the lead-wire losses, γ is 0.00229 w/°C for the EED with the stainless-steel lead wire and 0.00657 w/°C for the EED with the copper leads. Equilibrium temperatures for the two detonators with steady power input of 1 w while hanging free in still air are 465 and 153°C above ambient, respectively. Thermal time constants (C_p/γ) for the two detonators are 255 and 87 sec, respectively. These time constants, of course, are very much larger than those of any bridgewire systems of practical interest. Thus, for steady-state conditions, the temperature rise (θ) of the detonator, considered as a lumped thermal mass, must be added to that of the bridgewire system as calculated by using Equation (1) in its usual context.

Although it would be possible to combine Equation (1) for the bridgewire system with the same equation for the EED as a lumped thermal mass to obtain a somewhat more realistic prediction of its behavior, such an equation would be cumbersome and an oversimplification of the true situation. A rigorous representation would have to consider temperature distribution within the EED and in the surrounding media in terms of distributed parameters. In view of the complex configuration of initiator components and the variety of design, a general formulation for such consideration does not seem possible. A more profitable pursuit would seem to be the consideration of each general design as a unique system.

The condition assumed in the foregoing analysis, that of a detonator hanging free in still air, is unlike any anticipated for a weapon. EEDs used in weapons are usually inserted in relatively snug-fitting holes in metal fuze components. Under these conditions, the γ is somewhat difficult to assess because of its dependence on clearance, fuze-body materials, surface finishes, etc.; but it is safe, in general, to assume that the γ will be large enough so that the equilibrium temperature rise of the detonator body will be negligible.

However, a test for compliance with the 1 amp, 1 w, no-fire criterion, in the absence of specified procedures or test fixtures, is unlikely to be performed under service-installation conditions. (For many multipurpose items, a requirement for testing under such conditions would put the evaluation personnel in a quandary, and the test would probably be performed under the free-hanging conditions assumed above.) A designer forced to design for such conditions would have two alternatives: he could increase the heat capacity (C_p) sufficiently so that the 300 j would cause a manageable temperature rise, or he could increase γ enough to limit the equilibrium temperature rise to a reasonable value. In view of the small range of volumetric heat capacities of

solids (see Tables 1 and 2), the first alternative would be possible only by increasing the volume to several times that of the Mk 71 detonator (a change that would be quite unpopular with fuze designers). The second alternative could be attained by using sufficiently conductive lead wires. The 20-gage, 4 in. copper leads assumed above would be nearly sufficient. However, it should be pointed out that this calculation is based on the assumption that the ends of the lead wires are held at ambient temperature. Such an assumption is probably quite valid for most test arrangements, since relatively large clips are the most convenient and durable connections for test purposes. However, the compact, isolated electrical systems that are preferred in many designs to reduce electrical hazards may be relatively poor dissipaters of heat. Thus, a detonator designed to dissipate heat through its case might fail a 1 amp, 1 w, no-fire test, yet be appreciably safer in a fuze installation than one that passed the test because it was designed to dissipate heat through the lead wires.

To give realistic assurance of safety, a 1 amp, 1 w, no-fire test should be performed in a thermal environment that reasonably simulates conditions of use. In subsequent discussions it is assumed that the designer has sufficient control of specifications to assure that the EED will be tested in such an environment. If the initiator designer is given sufficient voice in the conditions of use to assure that the EED will be mounted in firm contact with an adequate heat sink, detonators much smaller than the Mk 71 can then be designed to comply with the specifications of Reference 1.

To assure adequate levels of safety against environmental electrical hazards and avoid expensive delays resulting from conflicting interpretations, a document such as Reference 1 should include unambiguous criteria defining the thermal characteristics of mountings and electrical circuits, for both use and testing of EEDs, that will comply with the 1 amp, 1 w, no-fire requirement or similar requirements.

DESIGN CONCEPTS AND ANALYSIS

All the designs considered herein involve a bridge—a small electrically conductive element heated by the passage of electricity to a temperature sufficiently high to ignite a flash charge of explosive or pyrotechnic material with which it is in close contact. The general types of bridges considered include "long" bridgewires, both round and flat, in which the most important path for the dissipation of heat is through the flash-charge explosive; "short" bridgewires, which lose most of their heat through their ends and terminals; and film bridges, in which the principal heat-loss path is from the bridge to an electrically insulating,

but thermally conductive, substrate to which the bridge is bonded. Although conductive-mix detonators seem quite promising as a solution to the general problem, they are not considered here because of their somewhat doubtful reputation in Navy activities, and because it is believed that a meaningful analysis would have to consider the statistical distribution of electrical and thermal conductors in relatively complex three-dimensional fields between electrodes. In addition to the bridge types, the effects of terminal, plug, and general initiator designs and of the composition and state of aggregation of flash-charge explosives are discussed.

LONG BRIDGEWIRES

For purposes of this discussion, a long bridgewire is defined as one that is long enough so that end effects are negligible in determining γ. Because metals are far better heat conductors than explosives or pyrotechnics, long bridgewires, in this sense, are exceptional. In most EEDs, the bridgewires are of intermediate length, in that both end and radial heat losses are significant. In most cases, radial losses to the flash-charge explosive are greater than end losses.

If it is assumed that the heat-flow pattern about a bridgewire is cylindrically symmetrical, the flux through any cylindrical surface is given by:

$$P_r = -2\pi r L k_f \frac{dT}{dr} \tag{9}$$

where

P_r = total heat flux through the surface

r = radius of the cylindrical surface

L = length of both the cylinder and the bridgewire

k_f = thermal conductivity of the flash-charge material

dT/dr = temperature gradient at the particular section

Rearranging and integrating gives

$$\frac{P_r}{\theta_r} = \gamma_r = \frac{2\pi Lk}{\ln D_2/D_b} \tag{10}$$

where θ_r is the temperature difference between a bridgewire of diameter D_b and a concentric cylindrical heat sink of internal diameter D_2, and γ_r is a heat-loss factor, which can be used in Equation (1).

Of course few, if any, practical initiators approximate the cylindrically symmetrical configuration to which Equation (10) applies. However, for any given design, it is possible to estimate an approximate effective value of D_2; or if experimental data are available that relate steady-state power sensitivity to bridgewire diameter for a given combination of hardware and flash-charge material, such data may be substituted in Equation (10) to obtain an estimate of the effective D_2 and the k_f.

A number of investigators have assumed that the γ of a bridgewire with a given explosive surrounding it can be characterized in terms of a surface coefficient of heat transfer, which can be multiplied by a temperature to obtain a bridgewire surface heat-flux density for no-fire, mean, or all-fire conditions (Ref. 17 and 18). Lynch and Allen (Ref. 18), for example, reduced data for lead styphnate flash charges with 1.5-4 mil bridgewires to no-fire watt densities ranging from 0.18 to 0.24 mw/mil^2 (averaging 0.2) and all-fire values ranging from 0.46 to 0.63 mw/mil^2 (averaging 0.54). For lead styphnate with bridgewires generally smaller than 1 mil in diameter, Kabik (Ref. 17) gives data that imply a mean threshold power density of about 2.5 mw/mil^2.

It may be noted that such experimental data as that of Lynch and Allen seem to discredit Equation (10), which is derived from heat-transfer considerations. It may be suggested that the apparently constant surface coefficients of heat transfer in experimental data result from the relatively small range of diameters used by any individual investigator, combined with the general tendency of each investigator to hold all other variables (including the bridgewire length) constant while varying the bridgewire diameter. If bridge length is held constant, end losses of heat increase faster (with the square of the diameter) than radial losses (directly as the diameter). Over a small range, this can almost exactly compensate for the decreasing effective surface coefficient with increasing diameter, predicted by Equation (10). If the data of Lynch and Allen for 1.5-4 mil bridgewires are adjusted for end losses by the methods described below for short and intermediate length bridgewires, the radial losses of heat are found to fit Equation (10) better than they do the constant-surface coefficient assumption (with or without end-loss adjustment). The thermal conductivity of lead styphnate obtained in these calculations was 0.955 $\mu w/mil\ ^\circ C$. This is similar to values given in Reference 11 for lead azide (1.64 $\mu w/mil\ ^\circ C$) and mercury fulminate (1.17 $\mu w/mil\ ^\circ C$). Lynch and Allen, in designing a film-bridge initiator (in which a metallic film was deposited on the surface of a ceramic rod, so that the surface exposed to the explosive remained cylindrical) based on their assumption of a no-fire watt

density of 0.2 mw/mil^2, calculated that a bridge 115 mils in diameter and 80 mils long should have a no-fire power of 10 w. However, they found that with a lead styphnate flash charge the highest no-fire level was only 1.6 w. The value calculated by Equation (10), using the constants obtained from their wire bridge data, is 1.49 w for the no-fire power level of the film-bridge initiator described in Reference 18.

No calculations are necessary to show that existing long bridgewire designs with explosives and loading practices now in use will not produce a detonator that will comply with the specifications of Reference 1 and still be usable with current guided missile fuze-firing circuitry. Numerous examples can be cited of detonators that have firing energy requirements several times that available from fuze circuits, yet will fire on a fraction of a watt. Equation (10) and Table 2 show that, of the factors affecting power dissipation, the one subject to the widest variation is the thermal conductivity (k) of the flash charge. Unfortunately, data relating thermal conductivities of explosive materials to state of aggregation are not at hand. However, to illustrate the effect that state of aggregation can have, magnesia brick has as much as 45 times the thermal conductivity of the bulk material, and vitreous magnesia is as much as 500 times more conductive than the powder (Ref. 9). In the case of lead styphnate, data at hand are not sufficient to reduce to the terms of Equation (10) the rather large difference between Kabik's results (Ref. 17) and those of Lynch and Allen, cited above. Undoubtedly part of the difference occurred because Kabik's data are based on experiments with smaller bridgewires. It is likely also that the variations between the configurations and materials used was involved, but it is probable that the largest part of the difference was the result of variations in the thermal conductivities of the materials used.

There is evidence that substantial changes in thermal conductivities of flash-charge explosives can be effected by compressing them at pressures on the order of 10 times those ordinarily used in such applications (Ref. 15). Metal additives might increase thermal conductivity still further. Note, in Equation (10), that γ, and hence the power necessary to raise the bridgewire temperature to any particular value, is exactly proportional to the thermal conductivity of the flash charge. EEDs of quite reasonable energy requirements and mean firing power on the order of 0.25 w are common. If, as seems probable, the thermal conductivity of the flash-charge explosive can be increased by a factor of 10 or so, the requirements of Reference 1 can be met with a detonator of ordinary design, which will also have quite reasonable energy requirements. Data indicate that increasing the thermal conductivity of a flash charge tends to reduce the energy requirement (Ref. 15).

It appears from the foregoing that it may be feasible to meet the requirements of Reference 1 with a detonator of conventional design,

wherein a substantial part of γ is attributable to radial heat flow from the bridgewire to the flash-charge explosive. An objection to all such designs is that the radial heat flow depends upon firm and close contact between explosive and bridgewire. This contact may be lost by any movement of explosive and bridgewire caused by environmental temperature changes, vibrations, accelerations, shrinkage of a beaded explosive charge from loss of solvent, local thermal decomposition, melting as the result of no-fire currents or pulses, or gradual relief of residual loading stresses. Such loss of contact can result in substantial decrease of γ and hence of the no-fire power or current. If a specification such as Reference 1 is to be relied upon to assure safety against premature functioning as the result of environmental radio frequency, it would seem that more positive and reliable heat-flow paths should form the basis of the no-fire conditions specified.

FLATTENED LONG BRIDGEWIRES

The assumption that the heat loss from a bridgewire to the flash-charge explosive can be characterized in terms of a surface coefficient of heat transfer suggests the use of a flat wire or ribbon to increase the surface area for a given cross section. There is no question that such systems can substantially increase γ without increasing the heat capacity of a bridge system, but it is safe to predict that the increase will generally be less than would be calculated on the basis of the surface coefficient assumption. The complexity of the heat-flow pattern about such a bridge discourages analysis at this time, but it is clear that the reduction in the divergence of the flow will result in a reduction of the effective surface coefficient. In itself, the flattening of a bridgewire seems an unlikely solution to the problem with which this report is primarily concerned. It might turn the trick if it were found possible to increase the thermal conductivity of a flash-charge material almost to the point where a long, round wire met the requirements. A flat bridgewire bonded to a thermally conductive substrate would be the equivalent of the film bridge discussed below.

SHORT BRIDGEWIRES

A short bridgewire is defined as one that is short enough so that radial losses are negligible in determining γ. Like long bridgewires, short ones are, in these terms, exceptional in current practice.

In a short bridgewire, as defined, only axial heat flow need be considered; and this, at any point in the wire, is given by the expression

$$p = \frac{-k_b A dT}{ds} \tag{11}$$

where

p = local rate of heat flow

k_b = thermal conductivity of the bridgewire material

T = temperature at any point

s = a given length of wire

If it is assumed that the ends of the bridgewire are connected to effective heat sinks at the same temperature, the temperature distribution will obviously be symmetrical, and the thermal gradient—hence, the heat flow—will be zero at the center. The heat flow through any cross section at a distance(s) from the center is equal to

$$p = \frac{sP_a}{L} \tag{12}$$

where

P_a = total power dissipated in the bridgewire

L = total length of the bridgewire

Combining Equations (11) and (12) and integrating gives

$$\frac{k_b A dT}{ds} = \frac{-sP_a}{L}$$

$$dT = -\frac{P_a sds}{k_b AL}$$

$$T_e = T_c - \frac{P_a}{k_b AL}\int_0^{L/2} sds = T_c - \frac{P_a}{k_b AL}\frac{L^2}{8}$$

$$T_c - T_e = \theta_m = \frac{P_a L}{8k_b A} \tag{13}$$

$$\frac{P_a}{\theta_m} = \gamma_a = \frac{8k_b A}{L} = \frac{2\pi D_b^2 k_b}{L}$$

where

γ_a = heat-loss factor

T_c = temperature at the center of the wire

T_e = temperature at the ends

θ_m = maximum temperature rise

The electrical resistance of the wire is, of course, given by

$$R_b = \frac{\rho L}{A} \tag{14}$$

where

R_b = resistance of the bridgewire

ρ = resistivity of the metal

combining Equations (13) and (14) gives

$$\theta_m = \frac{P_a R_b}{8 k_b \rho}$$

or

$$P_a = \frac{8 k_b \rho \theta_m}{R_b} \tag{15}$$

Equation 15 can be a useful design tool, since data on thermal conductivity and electrical resistivity are readily available for all bridgewire materials, and ignition temperatures can be estimated from available data or determined experimentally.

A glance at Table 1 will establish that, although $k\rho$ is far from constant for all metals, the range is hardly sufficient to be decisive in the choice of bridgewire materials. From the point of view of maximizing power dissipation with a given temperature rise, the best materials would be those with the highest $k\rho$, which are the high-resistance alloys.

For the highest of the values given (20.3 for Evanohm), assuming a 300°C temperature rise for safe no-fire, the bridgewire resistance would be 0.0488 ohm for 1 w no-fire. The current needed for 1 w at this resistance would, of course, be about 4.5 amp, which is close to the all-fire requirement of Reference 1. In other words, this resistance

approaches the limits shown in Figures 1 and 2. If a flash-charge material could be found with a no-fire level of about 1000°C, it would theoretically be possible to design a short bridgewire initiator that would comply with Reference 1. However, the dimensions of the bridgewire would be a bit unusual; for example, in order to have a resistance of 0.133 ohm, an Evanohm bridgewire would have to be 2 mils long if it were 1 mil in diameter, 8 mils long if it were 2 mils in diameter, and so forth.

Although techniques for the fabrication of such bridges could be developed, there would be a few problems. The dimensional problem could be alleviated by using a wire of lower resistivity, although the less favorable relationship of thermal or electrical conductivity of such materials would aggravate the electrical problem. A gold wire (assuming the 300°C no-fire temperature) would have to have a resistance of less than 0.0172 ohm, to meet the 1 w, no-fire requirement. Such a bridgewire would be 14 mils long if 1 mil in diameter, 56 mils long if 2 mils in diameter, and so on—dimensions easily attainable by present fabrication techniques. The current corresponding with the 1 w, no-fire level of a bridge of this resistance is more than 7 amp. An explosive with a no-fire temperature approaching 1000°C would not be very practical for use with gold, which melts at 1063°C.

It is possible that a high-temperature flash charge (if a material can be found that is satisfactory in other respects) in combination with a tungsten bridgewire might form the basis for a short bridgewire detonator that would comply with the requirements of Reference 1. Pure metals have quite high temperature coefficients of resistivity. The question naturally arises whether resistivities and resistance coefficients used in Equation (15) should be those at normal ambient temperature (20°C) or at that assumed for the no-fire or all-fire condition. The data at hand do not include thermal conductivities of metals of particular interest as bridgewire materials at elevated temperatures. However, the thermal conductivities of other pure metals change very much less than their electrical resistivities; in fact, they are only negligibly affected by the 300°C temperature changes associated with no-fire conditions. In Equation (15), resistance and resistivity changes cancel, so it is quite safe to use ambient temperature values with Equation (15) in the design of initiators.

A beneficial effect of the high temperature coefficients of pure metals when used for short bridgewires in attempts to comply with Reference 1 stems from the fact that resistances necessary to attain the 1 w no-fire requirement are well below the range permitted by other requirements (see Figures 1 and 2). Because of their high resistivity coefficients, such short, pure-metal bridges have much higher resistances at the all-fire condition, and thus approach the permissible resistance range.

Other advantages of the high resistivity coefficient will be apparent in the following section on short bridgewires with series resistors.

In Equation (13) the power requirement is proportional to the bridgewire area and inversely proportional to the lengths, whereas in Equation (3) the energy requirement is nearly proportional to the bridgewire volume. Thus, with a given wire, the power requirement is increased and the energy requirement decreased by reducing the length of the bridgewire. The power and energy sensitivities of short bridgewire initiators may thus be controlled by the designer quite independently of each other. The desired values may be substituted in Equations (3) and (13), or in (3), (14), and (15); these may then be solved simultaneously to obtain the bridgewire dimensions needed. Suppose, for example, a detonator is required with a 1 w, no-fire condition and a 50 percent firing energy of about 4500 ergs. From Equation (3)

$$D_b^2 L = 10$$

and from Equation (13), assuming a tungsten bridge,

$$\theta_m = 300 = \frac{(1)(L)(4)}{(8.0)(0.0037)D_b^2}$$

$$\frac{D_b^2}{L} = 0.144$$

Combining gives

$$\frac{D_b^2 L}{D_b^2/L} = L^2 = \frac{10}{0.144} = 69.5 \qquad L = 8.35 \text{ mils}$$

and

$$D_b^2 = \frac{10}{8.35} = 1.20 \qquad D_b = 1.1 \text{ mils}$$

The foregoing example illustrates, on the one hand, the simplicity of designing short bridgewire initiators, and on the other, the fabrication problems that may be encountered. The resistance of such a bridgewire would be about 0.015 ohm.

Short bridgewire initiators have the advantages of positive heat dissipation and independence between energy and power sensitivity.

However, the determinate relationship between power requirement and resistance makes it impossible for a short bridgewire initiator, using available alloys for bridgewires and using primary explosive flash charges, to meet the requirements of Reference 1. The development of higher temperature flash-charge materials might alleviate this difficulty. Another possibility is the insertion of a thermal barrier, such as a disc of mica, between the bridgewire and the flash charge.

SHORT BRIDGEWIRE WITH SERIES RESISTANCE

In the foregoing section, one of the most serious difficulties noted is that, when the resistance of a short bridgewire is low enough to raise the no-fire power to 1 w, the no-fire current is more than 5 amp. Another difficulty is that the resistances are so low that, from a fabricator's viewpoint, they result in rather difficult dimensions. Low resistances are also difficult to deal with electrically and may introduce new hazards. All these problems suggest the rather simple solution of designing a bridgewire with a no-fire current of 1 amp and adding sufficient series resistance to raise the overall resistance to 1 ohm. The no-fire input power of such a combination will, of course, be 1 w.

If, in Equation (15), power is expressed in terms of current and resistance,

$$P = I^2 R_b = \frac{8k\rho\theta}{R_b}$$

$$I = \frac{\sqrt{8k\rho\theta_m}}{R_b} \qquad (16)$$

where I is the current that will result in a temperature rise θ. By substituting values for gold in Equation (16), the IR product (which, incidentally, has the dimensions of voltage and indicates that, for short bridgewires, firing voltage is independent of bridge resistance) is 0.14 for 350°C, 0.17 for 500°C, and 0.24 for 1000°C. It would seem that a gold bridgewire should have a resistance close to 0.125 ohm to attain a 1 amp, no-fire condition. Because of the small range of $k\rho$ for pure metals (and alloys of medium resistivity), the relationship of peak temperature to the IR product is nearly independent of bridgewire material.

A few experiments have been performed to verify the above calculations and to develop design data applicable to a detonator that will comply with Reference 1. A preliminary attempt to fabricate initiators having 0.3 mil gold bridgewires with resistances close to 0.1 ohm resulted in a group with resistances varying from less than 0.1 to more than 0.2 ohm.

Tests of these with basic lead styphnate flash charges indicated that the threshold value of IR was close to 0.13 ohm-amp. The items with resistances between 0.08 and 0.11 ohm were apparently unaffected by exposure to 1 amp for 5 min.

A larger quantity of initiators made with similar materials was sorted into two categories. Those with resistances above 0.11 ohm were subjected to a steady current test by using the Bruceton technique, in which the test variable was the product of the measured cold resistance and the applied current. The mean threshold firing condition was 0.123 ohm-amp with a standard deviation of 0.047 log unit. The threshold temperature was 270°C (Equation (16)).

Another group was made with platinum bridgewires 1 mil in diameter. These were held very close to 0.1 ohm resistance, but of this, nearly half was in the terminals. In a steady-current Bruceton test, the mean threshold firing current was 1.69 amp with a deviation of 0.0144 log unit. This value is somewhat higher than the results obtained with the smaller bridgewires, but appreciably less than would be expected from Equation (16), on the basis of the 0.05 ohm resistance of the bridgewire itself. This intermediate value is probably attributable to the high resistance of the terminals. As predicted by Equation (7), this resistance is somewhat less than the perfect heat sink assumed in the derivation of Equation (16), assuming the 270°C threshold temperature implied above. The terminals could be considered extensions of the bridgewire for purposes of calculation with Equation (16), except that they were potted in an epoxy resin of appreciably higher thermal conductivity than that of the explosive.

These data tend to verify Equation (16), and indicate that a short bridgewire with series resistance may be a practical solution to the problem of developing a detonator of reasonable input energy requirement that will comply with Reference 1. As pointed out above, a combination bridgewire and flash charge with a 1 amp, no-fire characteristic, combined with sufficient series resistance to raise the total to 1 ohm, becomes a 1 amp, 1 w, no-fire device. Of course the series resistance increases the total energy requirement in proportion to the resistance increase, but as already noted, the energy and power or current requirements of short bridgewire initiators can be adjusted independently. The 0.1 ohm resistance indicated by Equation (16) and the experimental data cited above is combined with 0.9 ohm external resistance in the design shown in Figure 3. In such a system, to fire from a 10,000 erg input the combination bridge and flash charge must fire on 1000 ergs. The bridgewire shown in the figure is the result of a simultaneous solution of Equation (3) and the relationship of resistance to dimensions. Such bridgewires, when subjected to a steady current of 1 amp for 5 min,

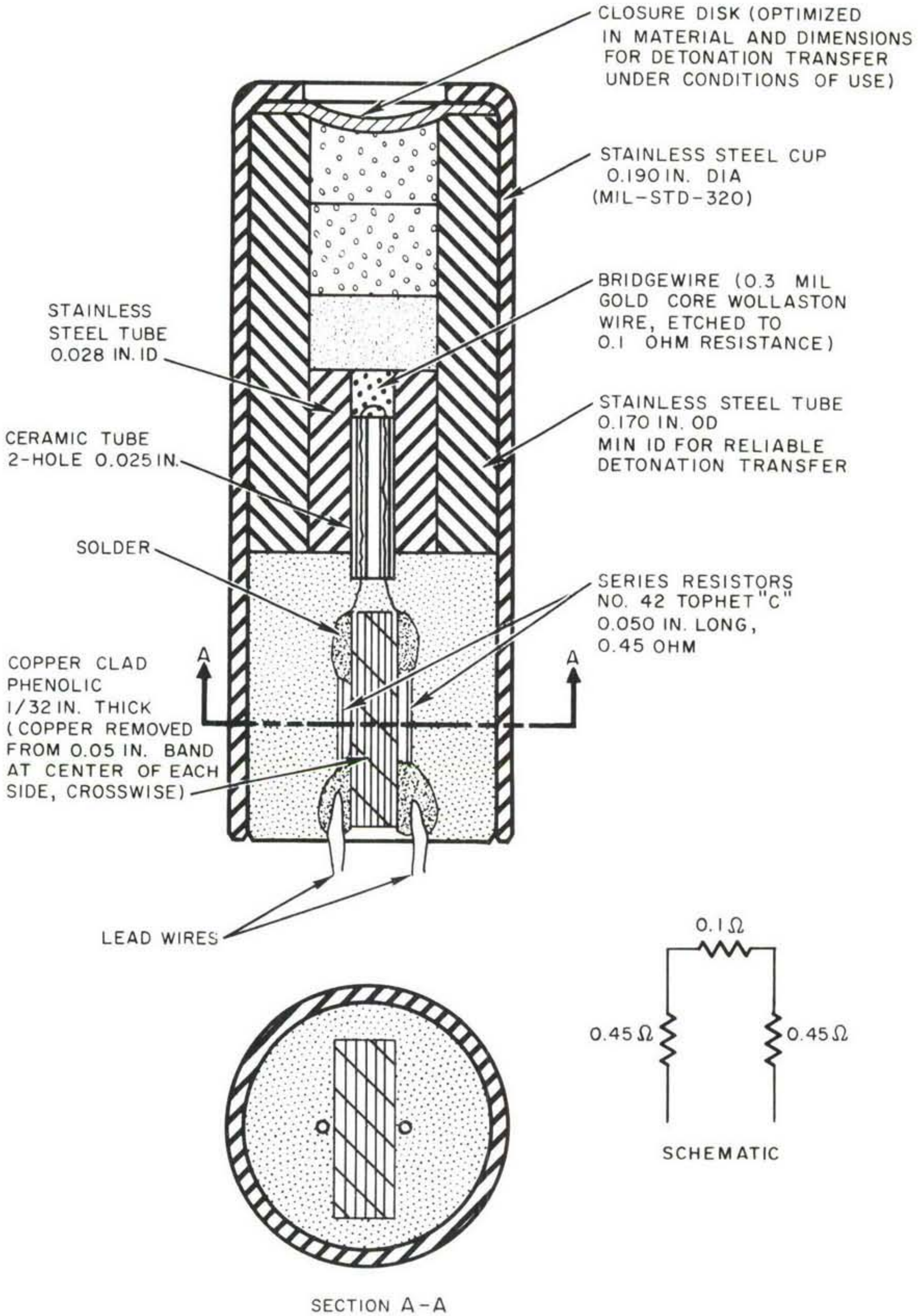

FIGURE 3. Proposed 1 amp, 1 w, No-Fire Detonator To Replace Mk 71 in Missile Fuzes

fired on a mean input energy of 472 ergs, which would indicate fair reliability with an input of 1000 ergs.

In an initiator with a short bridgewire and series resistance the high thermal coefficient of the electrical resistivity of a pure metal, which results in a higher bridge resistance under all-fire conditions than under no-fire conditions, in turn results in a greater proportional delivery of power or energy to the bridge under all-fire conditions than under no-fire conditions. Thus, for instance, if the effective resistance of the bridgewire of the detonator shown in Figure 3 is, when firing, 0.2 ohm rather than 0.1 ohm, the detonator will receive nearly 0.2 of the input power or energy rather than 0.1. This will result in improved reliability of the design, or allow a bit of leeway for the increase of the energy requirement, and consequently the bridgewire dimensions.

In such a design it is necessary to consider heat transfer from the series resistors as well as from the bridgewire. Rough calculations indicate that the use of a high-conductivity potting compound (conductivities as high as 0.0035 cal/sec cm °C = 0.037 mw/mil °C are claimed for certain epoxy resins) should limit the temperature rise of the solder joints between the bridge and the series resistors to less than 50°C, whereas ordinary potting compounds would allow this temperature to rise to a few hundred degrees.

An interesting possibility would be the use of stainless steel lead wires, like those used in the T24E1 and other Army detonators, as the series resistance of a short bridgewire initiator. Since the lead wires of the T24E1 have more than 1 ohm resistance, they would make a 1 amp, no-fire initiator into a 1 amp, 1 w, no-fire device, as well. Any objections to such a design would include the possibility of destroying the 1 w, no-fire characteristic by cutting the leads to a shorter length, or accidentally shortening them by breaking the insulation and making contact closer to the detonator than intended, and the need to provide a heat-conductive mounting for the detonator in order to control gross heating effects.

BRIDGEWIRES OF MEDIUM LENGTH

To rigorously compute the γ of a bridgewire of medium length would require the solution of a relatively complex differential equation, which would take into account the interaction of the effects of radial and end losses upon the temperature distribution, and hence interaction upon one another. However, the radial losses in a bridgewire of medium length are less than predicted by Equation (10), which is based on the assumption of a uniform temperature distribution, whereas the axial losses are more than predicted by Equations (13) and (15), since the temperature gradient near the ends is greater, relative to the ratio of

peak temperature to bridge length, than that of a short bridgewire. It is reasonable to assume that these losses are mutually compensating, so that the total losses are approximated by the sum of the axial and radial losses, as predicted by

$$\frac{P_t}{\theta_t} = \gamma_t = \frac{2\pi L k_f}{\ln D_2/D_b} + \frac{2\pi k_b D_b^2}{L} \tag{17}$$

or

$$P_t = \frac{2\pi L \theta_r k_f}{\ln D_2/D_b} + \frac{8 k_b \rho \theta_m}{R_b} \tag{18}$$

Possibly the optimum solution to the problem with which this report is concerned will be a design in which heat dissipation is maximized by combining radial and axial losses in a bridgewire of medium length.

FILM BRIDGES ON THERMALLY CONDUCTIVE SUBSTRATES

The formation of bridgewires by deposition of an electrically conductive film on an insulating substrate has been the subject of wide interest for many years. Films have been deposited by vacuum evaporation, sputtering, chemical, electrochemical, and "writing" techniques, and as paints, glazes, "dags," and inks. Stencils, masks, and photographic techniques have been used to control the pattern of the film. But the only film bridges that have been used in standard ordnance initiators are the graphite bridges formed by the evaporation of water from Aquadag,[1] a colloidal suspension of graphite in water. This is the only type of initiator specifically prescribed by Reference (1). However, film bridges offer interesting theoretical possibilities, as will be shown.

If the heat flow from a limited area on the surface of a relatively large mass is considered, it is evident that the flow will tend to approach spherical divergence. In spherically divergent flow, the flux through any spherical surface is given by

$$P_s = -k_p A \frac{dT}{dr} = -k_p 4\pi r^2 \frac{dT}{dr}$$

[1] Aquadag is a registered trademark of Acheson Colloids Co., Port Huron, Michigan.

which, after being rearranged and integrated, gives

$$4\pi k_p dT = -P_s \frac{dr}{r^2}$$

$$4k_p \theta_s = P_s \int_{r_1}^{r_2} \frac{dr}{r^2} = P_s \left(\frac{1}{r_1} - \frac{1}{r_2}\right)$$

but since r_2 is much greater than r_1, its reciprocal becomes negligible, and

$$P_s = 4\pi k_p \theta\, r_1$$

where P_s is the total heat flux in a spherically divergent flow; and θ is the temperature drop from a small spherical surface of radius r_1 to a much larger, concentric, spherical surface of radius r_2 or, more generally, the difference in temperature between a point at distance r from the center and a remote point. The heat flux per unit area (p) is given by

$$p = \frac{4\pi\theta k_p r_1}{4r_1^2} = \frac{k_p \theta_s}{r_1} \tag{19}$$

Of course the heat flow in a substrate very close to a heat-emitting film is complex and the spherical flow is an approximation. If it is assumed that the effective center of the spherical flow from a film of square outline is at a distance from the corners equal to the side (s) of the square, the temperature at the corners (θ_v) is given by

$$\theta_v = \frac{P_s}{k_p s}$$

But the center of such a flat surface is closer to the center of the sphere than the corners (in this case the distance at the center (h) is $s\sqrt{2}$), so the temperature rise at the center of the film (θ_c) with respect to remote points in the substrate is

$$\theta_c = \frac{P_s}{\sqrt{2} k_p s}$$

and since the effects of variations of film configuration may be expected to be reasonably self-compensating if the configuration is not too radically different from square, a reasonable approximation of the maximum temperature rise (θ_m) of a film of area A is given by

$$\theta_m = \frac{P_s}{k_p \sqrt{2A}} \tag{20}$$

and γ would be

$$\frac{P_s}{\theta_m} = \gamma_s = k_p \sqrt{2A} \tag{21}$$

Assuming a safe no-fire temperature of 300°C, Equation (20) can be converted to a design formula for 1 w, no-fire

$$A = \frac{P_s^2}{2k_p^2 \theta^2} = \frac{(1000)^2}{2k_p^2 (300)^2} = \frac{5.55}{k_p^2} \tag{22}$$

Power is expressed in milliwatts so that the thermal conductivities given in Table 2 may be used directly. To design a bridge that will also fire reliably on 10,000 ergs (from Equation (3), assuming that the same relationship exists between volume and energy requirements in film bridges as in wire bridges and also that the all-fire energy is twice the 50 percent point), the volume should be limited to about 8 mils^3. To make the 1 amp level coincide with the 1 w level, a resistance of 1 ohm is desirable. Table 3 gives some film bridge dimensions, calculated by using the foregoing considerations, which should result in initiators that comply with Reference 1 and could be substituted in many currently used guided missile fuze systems. As the table shows, the squaring of the thermal conductivity of the substrate material in Equation (22), in combination with the wide range over which thermal conductivities vary (see Table 2), limits the choice of substrate materials to relatively few. At the one extreme, beryllia is such a good thermal conductor that it is questionable that a film bridge of reasonable dimensions would fire a flash charge on 5 w. The dimensions of the film on alumina are essentially those of flat wires. If an intimate and reliable bond between such a bridge and an alumina substrate can be formed, it may become the basis for a rather good solution to the problem. The wirelike dimensions result from the specification of 8 mils^3 as the volume. If the thickness and length are reduced and the width is increased, the resistance and contact area can be maintained and the volume reduced, thus approaching a configuration more aptly described as a film. It is

TABLE 3. Dimensions of Film Bridges

Dimensions are in mils.

Substrate	Film Area	Film Thickness	Gold Film[a]		Platinum Film[a]	
			Width	Length	Width	Length
Alumina	22.2	0.36	0.244	91.5	0.49	45.4
Beryllia	0.2	40 (This is ridiculous!)				
Mullite	2222	0.0036	24.4	91.5	49	45.4
Glass	9650 (max k_p)	0.00083	105	91.5	197	45.4
Nylon	165,000	0.0000484	1800	91.5	3680	45.4

[a]The resistance of both the gold and platinum wires will remain unchanged if the width is increased by the same factor (up to $\sqrt{5}$) as the length is decreased.

possible that such a reduction in volume may be necessary to attain the 10,000-erg all-fire characteristic because of the very short cooling time of a small bridge with such a high Y. Some reduction in firing energy would improve the reliability of the detonators in guided missile applications without affecting safety, particularly if the reduced energy were accompanied by an increase in threshold firing current (which would decrease its susceptibility to environmental RF initiation) and a decrease in resistance (which would decrease susceptibility to initiation by static electricity). Other ceramics that have thermal conductivities similar to alumina, and thus would require similar film areas to dissipate 1 w, include oxides of magnesium, tin, zinc, copper, thorium, and cerium.

The dimensions of a film on a mullite substrate are nearly ideal for some application techniques. Porcelain and similar materials have thermal conductivities in the same range as mullite, and it is possible to compound plastics (Ref. 15, 16) with thermal conductivities in this range and higher by the judicious choice of fillers. The vitreous ceramics would seem preferable for film-bridge substrates, because their thermal coefficients of expansion match those of metals more closely, and because they can be expected to be relatively free of "outgassing" in vacuum evaporation and sputtering techniques of film application. On the other hand, for "films" of electrically conductive plastics, the high thermal conductivity plastic substrates would be ideal. The initiator plug shown in Figure 4 was designed to meet safety requirements by using Equations (3) and (22).

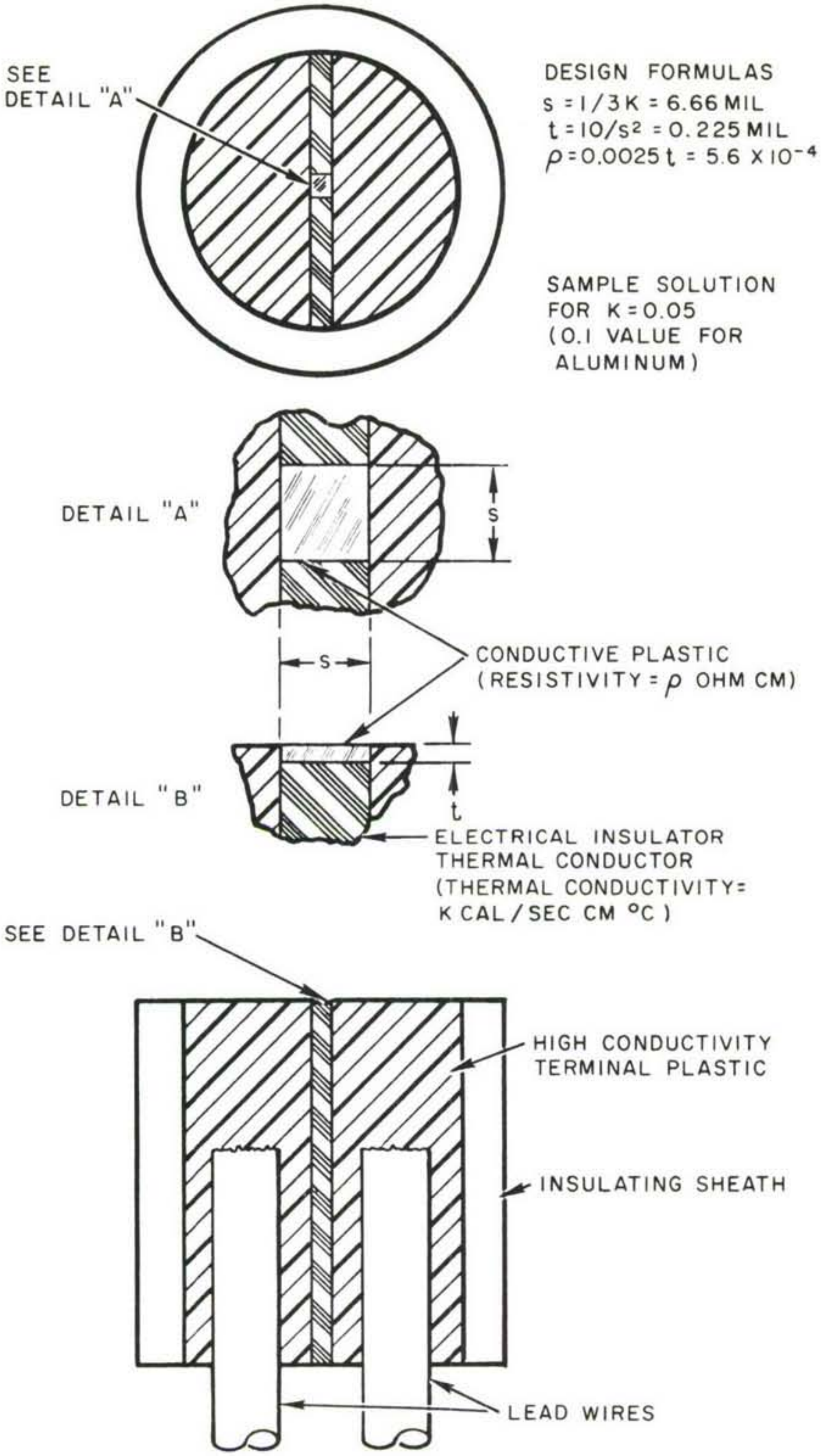

FIGURE 4. Suggested EED Plug Using Conductive Plastics To Attain 1 amp, 1 w, No-Fire and 10,000 erg All-Fire

The area necessary for films on glass substrates is close to the maximum that could fit into a detonator the size of the Mk 71. It probably violates the assumption upon which the derivation of Equation (22) is based—i.e., that the film is of small extent compared with the substrate.

The dimensions necessary for a film bridge on a nylon substrate were included mainly to illustrate how useless unmodified plastics are for this application. Moreover, Table 2 shows that most plastics have appreciably lower conductivities than nylon; therefore, much larger contact areas would be needed.

A suggested approach to a low-energy, high-current detonator (Ref. 19) is that of applying a film bridge to an anodized aluminum substrate. In such a system, if the anodized layer is thin compared with the width of the film bridge, the temperature drop between the film bridge and the opposite side of the anodizing becomes

$$\theta_a = \frac{Pt}{kA} \tag{23}$$

where θ_a is the temperature drop across the anodized layer and t is the thickness of the layer. The temperature drop from the point on the anodized surface opposite the center of the film bridge and a remote point in the aluminum plug would be given by Equation (21), and the total temperature drop between the bridge and remote points of the detonator body would be the sum of these temperature drops. These equations could be combined to form a quadratic, but since aluminum has about ten times the conductivity of alumina, it is obvious that the temperature drop through the anodized layer must be several times that through the aluminum. The simplest way to calculate the area, therefore, is to solve Equation (3) for a somewhat lower temperature drop, for example 250°C, which gives an area of 8 mils^2 when substituted in Equation (23). If this area is substituted in Equation (20) along with the conductivity of aluminum, the drop from the point in the aluminum under the center of the film bridge to a remote point is 47°C, and the total drop is very close to 300°C, which has been the assumed no-fire temperature in most of these calculations. The 8 mils^2 may be compared with the 22.2 mils^2 for a solid alumina substrate. This scheme increases γ appreciably. From Table 3, it would seem that the thermal conductivity of alumina is adequate for current purposes; however, it is quite possible that fabrication or other considerations might result in a preference for the anodized aluminum plug design.

The same approach can be used to evaluate the effect of a layer of bonding agent between a film or ribbon bridge and a substrate of higher conductivity than the cement. If, for example, epoxy resin with a thermal

conductivity of 0.04 mw/mil°C is used to bond such a bridge to alumina, the area necessary to dissipate 1 w at 300°C comes to about 140 $mils^2$. Assuming that 8 $mils^3$ is an appropriate volume for the 10,000 ergs, the thickness of the film comes to 0.057 mil and, for the resistance range of 0.2 to 0.1 ohm, the other dimensions of a gold film bridge would range from 40 mils long by 3.5 mils wide to 90 mils long by 1.5 mils wide, and for platinum films, from 20 mils long by 7 mils wide to 45 mils long by 3.1 mils wide. Such dimensions seem to fall within the range for which reasonable fabrication techniques might be devised. Of course, there is some question as to whether the epoxy resin would retain its properties under specified no-fire conditions. Other cements, particularly silicones, ceramics, vitreous enamel, and other inorganic adhesives, should be investigated for this purpose.

PLUG AND TERMINAL DESIGN AND MATERIALS

In the foregoing discussion of film bridge initiators, the thermal conductivity of the plug was shown to be the most critical variable. For other types of initiator, the relationship is somewhat less direct, but still quite important. In a short bridgewire, the calculations are based on the assumption that the terminals are effective heat sinks, which remain so at ambient temperature. The validity of this assumption rests on the implied assumption that the γ from the inner ends of the terminals is sufficiently large to keep the temperature at least reasonably close to ambient. The second-order differential equation relating the γ to dimensions and conductivities of plugs and terminals is not difficult to solve, but satisfactory insertion of boundary conditions has not been accomplished at the time of this writing.

The temperature drop between the inner face of the terminal and the case of the detonator can be approximated by assuming it to be the sum of the drop through that portion of the terminal (or lead) wire that is molded into the plug (which may be calculated by means of Equation (7)) and the radial drop from the wire to the case through the plug (which may be calculated by using Equation (10)). By applying this approach to the plug used in the Mk 71 detonator and assuming that 0.5 w is carried off in each terminal, the temperature drop through the bridgewire is 50°C and that through the plug (assuming its thermal conductivity to be 0.01 mw/mil °C) about 100 °C. This 150° must be subtracted from the no-fire temperature of the explosive to obtain the permissible temperature differential between the center and ends of the bridgewire. An increase in thermal conductivities of plugs and terminals would make it possible to design for higher temperature drops in the bridgewire and allow somewhat higher bridge resistances. If the thermal conductivity of the plug is reduced sufficiently, and if a good thermal contact is

established between the terminal and the plug, the terminal wire might serve quite usefully as the series resistance with a short bridgewire.

In a long bridgewire, the effect of the plug is still more indirect, but the plug undoubtedly contributes significantly to the γ, particularly in a "flush-bridge" initiator like the Mk 71 detonator. A long bridgewire, flush-bridged on a plug of high thermal conductivity (such as alumina or the carbonyl iron that has been employed as an RF attenuator) is an interesting possibility for the applications considered herein, particularly if it is used with an explosive of good thermal conductivity.

CHOICE OF FLASH-CHARGE EXPLOSIVE AND LOADING CONDITIONS

As stated earlier, the assumption of a more or less fixed ignition temperature as a property of a particular explosive is an approximation that greatly simplifies calculations. However, this approximation should not be relied upon too quantitatively (Ref. 3). For instance, if the heat capacity of the bridge system is considered to be that of the bridgewire itself, the threshold firing temperature of lead styphnate (under pulse firing conditions), as implied by Equation (3), is higher than 1000°C, whereas steady-current firing data imply a much lower threshold temperature. In terms of the more basic consideration that initiation results when the sum of the input power and the rate at which energy is liberated by the explosive exceeds the rate at which it is dissipated, and in combination with chemical kinetics, the threshold temperature for pulse firing should be higher than that for steady-state firing. It might be argued that the success of Equation (1) in predicting the behavior of initiators (to which it has been applied in extensive experiments) tends to support the supposition that a fixed initiation temperature is a real property of an explosive. However, adjustment of the heat capacity and γ to fit experimental data could mask this difference. Thus, Equation (1) could be a highly successful empirical relationship, yet misrepresent the true situation. Although a quantitative analysis will not be undertaken at this point, it is quite clear that this difference in temperatures would be expected to vary greatly with the thermal properties of the initiator system and the kinetic properties of the flash-charge material. It is suspected that the choice of the Mk 1 squib for the extensive experiments in the application of Equation (1) was fortuitous in this respect. Initiators of the characteristics that would comply with safety requirements and yet fire on a pulse of reasonable energy content might be expected to have larger differences in these temperatures, since the combination of a small heat capacity and a large γ would result in very short cooling times. This difference would be further increased in such systems as short bridgewires and film bridges, in which most of the heat loss is to inert parts rather than to the explosive.

Explosives of high activation energy increase their reaction rates more sharply with rising temperatures, so that their effective ignition temperatures vary less with conditions. Of the commonly used primary explosives, normal lead styphnate has an unusually high activation energy and might be the ideal explosive for use in short bridgewire and film bridge initiators.

The basic lead styphnate used in the experiments was chosen because a dried supply of this explosive was at hand and it was expected that it would behave similarly to normal lead styphnate. It is hoped that the very low threshold temperature implied from the steady-current tests, combined with the high temperature implied by the pulse-firing tests is evidence that this material has a much lower activation energy than that of normal lead styphnate. If so, it may turn out that normal lead styphnate will have a higher threshold steady-current requirement, but a similar or lower pulse-firing energy requirement.

It is probable that heat transfer considerations account for at least some of the effects that have been related to reaction kinetics in the previous paragraph. It has been observed (Ref. 20) that energy requirements for pulse firing of initiators loaded with both lead and silver azide decreased progressively as the loading pressure was increased, so that the average value for explosives pressed at 90,000 psi was about a third that for the materials pressed at 3,300 psi in otherwise identical devices. The only reasonable explanation of this that occurs to the writer is that the higher thermal conductivity resulting from the higher loading pressure causes a large fraction of the energy delivered to the bridgewire to be transferred to the explosive rather than back to the terminals. If this is true, perhaps both the increased current requirement and the decreased pulse energy requirement, which are desirable for the purposes with which this report is concerned, can be obtained by the use of explosives with high thermal conductivities. The investigation of the effects of explosive composition and loading techniques upon thermal conductivities of primary explosives may be expected to yield data of value in the development and design of improved EEDs.

SUMMARY

By the application of the heat-transfer considerations discussed, it is possible to design electroexplosive devices with a wide range of input characteristics. The relationship between threshold firing power is by no means direct; in fact, for some circumstances it may be inverse. The full application of the design techniques outlined will depend upon the accumulation of more complete data on the heat-transfer properties of primary explosives and the development of techniques for the fabrication of initiators from the materials and with the dimensions indicated by the calculations.

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2. Guided missile fuzes - Detonation

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